

Past and future change in global river flows

Lukas Gudmundsson¹✉, Manuela I. Brunner^{1,2,3}, Petra Döll^{4,5}, Etienne Fluet-Chouinard^{1,6}, Natalia Frolova⁷, Simon N. Gosling⁸, Yukiko Hirabayashi⁹, Maria B. Kireeva¹⁰, Xiaomang Liu¹¹, Hannes Müller Schmied^{4,5}, Dmitriy Magritskiy⁷, Louise J. Slater¹², Lina Stein^{13,14}, Yves Tramblay¹⁵, Kaiwen Wang¹¹, Conrad Wasko¹⁶, Dai Yamazaki¹⁷ & Xudong Zhou^{17,18}

Abstract

Rivers are a vital component of the global water cycle. However, human influence on climate and terrestrial systems is increasingly shaping river flow regimes. In this Review, we summarize the current understanding of past and projected changes in global river flow, focusing on annual volumes, seasonal dynamics and sudden changes. River flow observations reveal distinct regional trends, including increased flows in high-latitude regions and decreased flows in parts of the mid-latitudes and subtropics. Snow-dominated regions in particular show shifts in their seasonal cycle towards earlier flows. These patterns align broadly with historical climate model simulations, suggesting an anthropogenic climate change signal. However, attribution is complicated by the interplay of greenhouse gas emissions, CO₂-driven vegetation response, land-use change and water management. Future projections indicate continued change, with certain regions experiencing wetter conditions and others intensified drying. Seasonal changes, particularly those due to altered snow dynamics, are also expected to intensify. Despite modelling and observational advances, uncertainties remain regarding the combined effects of anthropogenic climate change and direct human interventions in terrestrial systems. Closing these gaps requires improved monitoring, advances in modelling and robust attribution frameworks, in support of efficiently managing water resources, sustaining ecosystems and adapting to a changing climate.

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Introduction

Rivers and streams are key components of the global water cycle, transporting approximately 46,000 km³ of water from the land to the oceans each year, which corresponds to approximately 40% of all terrestrial precipitation^{1–3}. River flow and stream flow are the result of a cascade of processes that includes the storage of precipitation on land and its subsequent release back to the atmosphere as evapotranspiration or as runoff into the rivers. River flow is not only determined by atmospheric boundary conditions, but the dynamics of terrestrial water fluxes are modulated by processes that depend on land properties including topography, soil texture or vegetation cover.

Humans are altering the Earth system at an unprecedented rate, affecting the global water cycle and thus river flow^{1,4,5}. Human emissions are changing the composition of the atmosphere, and climate models project that global runoff will increase by approximately 3% for each degree Celsius of global warming⁶, albeit with distinct wetting and drying regions around the world^{7–10}. Meanwhile, human water and land use can affect terrestrial water systems, either directly, through water withdrawals, reservoir construction and riverine engineering – or indirectly, by altering the landscape properties that control the partitioning of incoming precipitation into evapotranspiration and runoff^{1,11–13}. In total, human water use is estimated to amount to 24,000 km³ per year^{1,3}, which is more than half of terrestrial discharge. Although withdrawn water is usually returned to the system through processes such as irrigation, human water usage has an outsized role in the terrestrial component of the global water cycle.

Assessments of past^{14–22} and future^{23–28} changes in river flow indicate distinct regional responses to anthropogenic climate change^{7,12,18,29} as well as water and land use^{12,30,31}. However, in many cases, the relationship between observed changes in river flow and anthropogenic drivers is less clear. Past and future changes in river flow have often been studied from differing disciplinary perspectives, resulting in a fragmented body of literature on river flow trends. Efforts to identify drivers at the global scale often focus on the effects of individual factors such as water and land management^{31–33} or the effect of anthropogenic climate change^{18,29,34}. However, study designs typically emphasize the role of the focal driver (such as water management or anthropogenic climate change), thereby complicating a comprehensive assessment in light of for substantial natural climate and environmental variability^{35–37}. Moreover, there is a plethora of case studies that provide a detailed assessment of trends for individual river basins^{38–41} but do not allow for generalizable conclusions.

This review aims to consolidate the knowledge on past and future changes in river flow, with an emphasis on the processes and phenomena that are relevant at continental-to-global scales. We focus on changes in annual mean and seasonal river flow, as changes in both wet^{42,43} and dry⁴³ extremes have been addressed elsewhere. To summarize existing knowledge on how human influence on the Earth system can affect river flow, a water balance perspective is taken to review the mechanisms related to anthropogenic climate change, the influence of elevated CO₂ on plant transpiration, land-cover and land-use change, and water management. Past changes are then presented, including trends in annual flow magnitude, shifts in the seasonal cycle and abrupt changes in river flow dynamics. This retrospective perspective is mirrored by an assessment of how river flow is projected to change in a warming climate. The paper concludes with a synthesis of the key findings and highlights aspects of global river flow change that require further research.

River processes and human interactions

River flow is generated by a combination of processes that determine the local terrestrial water balance and the lateral redistribution of water along hillslopes and river networks^{1,44,45} (Fig. 1). In this context, the term ‘local’ indicates small land units that receive and store precipitation and then release water as both evapotranspiration to the atmosphere and as runoff to the river network. Different classes of processes – and thus different drivers of change – control the local terrestrial water balance as well as the routing of water through the river network. Anthropogenic climate change, the effect of CO₂ fertilization on plant transpiration, land-use and land-cover change primarily affect the local water balance. In contrast, water management can affect river flow both locally through effects on runoff as well as regionally along the river network.

River flow processes

Local runoff is pragmatically defined as the gravity-driven flow of water above and below the land surface that exceeds the capacity of land to absorb or retain water, and often moves towards river channels. Runoff (R) is the residual of the local terrestrial water balance

$$R = P - E - dS/dt \quad (1)$$

that accounts for water input through precipitation (P), water loss through evapotranspiration (E) and changes in the amount of water stored over time (dS/dt). Water storage compartments include snow and ice, surface water bodies, soil moisture, groundwater and water stored by plants. The dynamics of runoff and evapotranspiration are thus determined by the state of different water storage compartments and the drivers of evapotranspiration, which include net radiative energy and the water vapour deficit. Although runoff dynamics are driven by atmospheric boundary conditions, they are also modulated by land properties that include, but are not limited to topography, the water-holding capacity of soils and vegetation cover.

Runoff across landscapes converges to form and flow into rivers and streams. Flow along the river network follows a gravity-driven wave that is modulated by factors such as channel bathymetry, slope and water retention in the floodplain, wetlands, lakes and artificial reservoirs. Rivers can either be replenished by or infiltrate the underlying groundwater^{46,47}. It is estimated that 50–60% of the river segments on Earth cease to flow at least 1 day per year^{48,49}. Although natural stream flow intermittence is most prevalent in semi-arid and arid regions, where it might occur even in large rivers, it is also widespread in smaller headwater streams across humid regions⁵⁰. Eventually, water flowing in rivers is transported to the oceans or inland sinks.

Anthropogenic climate change

Human emissions of greenhouse gases and aerosols are modifying the composition of the atmosphere and thereby affect the Earth’s radiative forcing and energy budget^{51,52}. The resulting changes in the climate system affect the global water cycle^{3,8,53} and the cryosphere^{54,55}, with possible implications on global river flow. Human influence on the climate system can thus affect the local water balance and hence runoff and river flow through changes in precipitation, the atmospheric drivers of evapotranspiration and the effect of warming conditions on the cryosphere.

Global precipitation is expected to increase in response to anthropogenic climate change due to higher evaporation rates over the oceans and a greater water-holding capacity of warmer air^{3,8}. However, cooling effects of aerosols, rapid adjustments to radiative forcing and

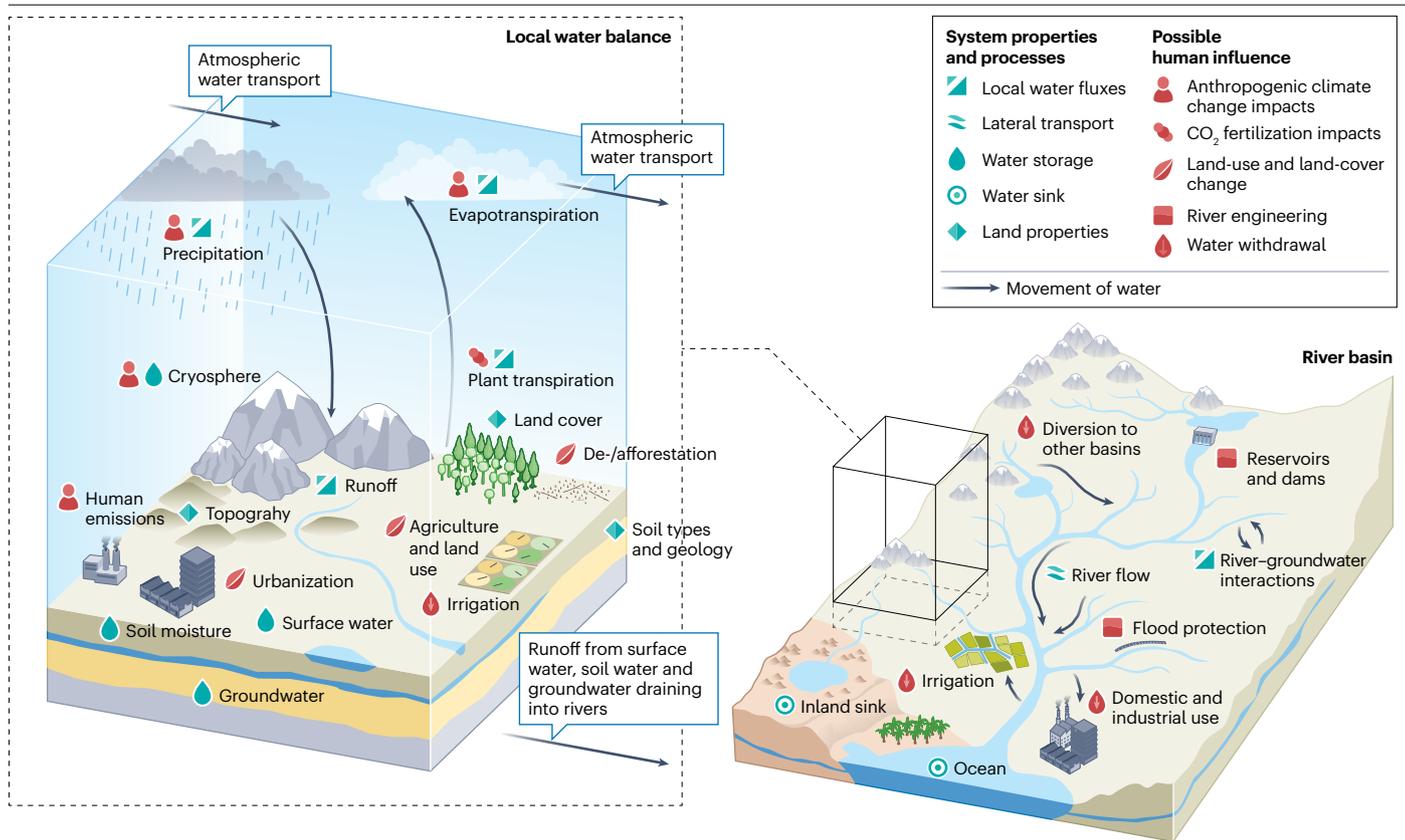


Fig. 1 Processes and drivers of river flow. River flow originates from water balance processes that determine how precipitation is partitioned into evapotranspiration, terrestrial water storage and runoff. These processes are driven by local atmospheric conditions and modulated by properties of the

terrestrial system and local human activities. Runoff drains into rivers and is then routed along the global river systems to the oceans or inland sinks. The resulting river flow aggregates local runoff and in-channel flow is modulated by river-bed properties and human interference along the river channel.

observational uncertainties make it difficult to detect the increase in global precipitation in the observed record^{3,8}. As precipitation is also modulated by large-scale atmospheric circulation, it is not changing uniformly across the globe, with distinct wetting and drying regions that are detectable in the observed record and can be summarized along a latitudinal pattern^{56–59}. Over the past decades, annual precipitation tended to increase in the tropics and at high latitudes, whereas it decreased in mid-latitudes in response to human influence on the climate system. Similarly, climate models project that annual precipitation at high latitudes will probably continue to increase, whereas the middle latitudes and the tropics are expected to experience a combination of drying and wetting^{8,60–62}, albeit with notable spread across model simulations that is most pronounced in tropical regions¹⁰.

Evapotranspiration has increased across the world during the past decades^{8,63–65}, probably as a result of human influence on the climate system^{8,64–66}. The change is driven by an increasing water-holding capacity of warmer air, changes in near-surface radiative energy and modulated soil moisture⁸. In densely populated regions, past evapotranspiration trends might have been more strongly influenced by anthropogenic aerosol emissions than by greenhouse gas emissions⁶⁷. An increase in future evapotranspiration is projected for a large fraction of the global land area^{8,62,68,69} and with smaller differences across models compared with precipitation¹⁰. The difference between

precipitation and evapotranspiration ($P - E$) averaged over multiple years is projected to increase in high-latitude regions, tropical Africa and South Asia. A decline in $P - E$ is projected for several regions, including Central America, tropical South America, the Mediterranean and southern Africa^{70–72}.

Observed declines in global soil moisture are probably due to changes in precipitation and evapotranspiration resulting from anthropogenic climate change, although there exists considerable uncertainty^{73–76}. Past trends in soil moisture vary spatially, and regional trends differ across data sources^{773,778}. Climate models project decreasing global mean soil moisture and terrestrial water storage in a warming climate, albeit with strong regional differences and a dependence on soil depth in the direction and magnitude of change^{8,74,79,80}.

Both seasonal snow cover and mountain glacier mass have declined substantially over the past century^{81–84}, which can be attributed to increasing temperatures due to anthropogenic climate change^{85–88}. Climate models project a continued decrease in both seasonal snow cover and mountain glacier mass^{81,83,89}, which is particularly relevant for stream flow in high latitudes.

Influence of elevated CO₂ on plant transpiration

Beyond its role in driving global warming, increasing atmospheric CO₂ can also affect plant transpiration and thus the local water

balance. Increasing atmospheric CO₂ leads to a reduced need of plants to open their stomata for photosynthesis, which in turn decreases transpiration⁹⁰. However, increasing atmospheric CO₂ also fosters vegetation growth, higher biomass and an increase in plant transpiration^{90–92}. Over the past decades, vegetation greenness has increased, probably due in part to CO₂ fertilization⁹³. This greening has been related to increased evaporation^{91,93,94} and to decreasing river flow in water-stressed climates⁹⁵. Conversely, global-scale analyses⁹², confronting model estimates with observed changes in river flow⁹⁶ as well as future runoff projections⁹⁷ find only limited physiological effects of elevated atmospheric CO₂ concentrations on plants and highlight large model uncertainty⁹⁷.

Land cover and land-use change

Humans have affected about three-quarters of the global ice-free land area through a wide range of activities including the conversion of forests into farmland or urbanization^{98,99}, with implications for terrestrial water dynamics^{1,100,101}. Land cover and vegetation affect the rate at which water is transported to the atmosphere through both physiological and biophysical mechanisms. However, the net effect of vegetation on evapotranspiration and runoff is subject to discussion and can depend on the antecedent environmental and climate conditions^{102–105}. Nonetheless, global-scale assessments indicate that increasing forest cover or leaf area index are associated with higher evapotranspiration rates^{91,106,107}. Similarly, it was found that deforestation is associated with increasing river flow, an effect that is more pronounced in water limited areas and less apparent in snow dominated climates¹⁰⁸. Large-scale re-vegetation of the Loess Plateau¹⁰⁹ and increasing vegetation activity in the Mediterranean¹¹⁰ are associated with decreasing runoff volumes.

Urban expansion and the laying down of impervious surfaces affect regional water balance by increasing runoff and thus river flow. Increasing urbanization is associated with increasing annual maximum flood extent¹¹¹ and increasing runoff volumes^{105,112–114}, with some evidence suggesting that the effects are larger for catchments that are more urbanized to begin with¹¹⁵.

Water management

Water management can influence river flow through a variety of means, including withdrawals, construction of reservoirs, water diversions¹¹⁶, channelization, floodplain management and wetland drainage. Here, we place a focus on the withdrawal of water and the construction of dams as two of the most prevalent and impactful methods of water management.

Water is abstracted by humans from surface and groundwater predominantly for irrigation, as well as for domestic and industrial use^{101,117,118}. After usage, withdrawn water can either re-infiltrate, be transferred to other river basins^{119,120}, be re-fed into the river further downstream or contribute to evapotranspiration. Abstractions from groundwater can result in declines in the water table, evapotranspiration and surface water availability^{121,122}, but can also have the opposite effect when the water is used for irrigation. Globally, irrigation accounts for about 70% of all water abstractions¹¹⁸ and continues to expand¹²³. The increases in surface soil moisture resulting from irrigation can lead to increased evapotranspiration rates^{118,124} and a reduction in water availability and regional river flow volumes^{30,110}. Model-based studies estimate that water abstractions reduce global annual river discharge to the oceans and inland sinks by 2–3%^{32,101,125,126}, although there are substantial regional differences.

Reservoirs and dams have crucial roles in flood control, sustaining populations, hydropower generation and irrigation. The number of dams steadily increased throughout the twentieth century, leading to a fragmentation of the global river network^{127–130}. It is estimated that approximately half of the world's largest rivers are affected by dams¹³¹ and are thus not free flowing¹³². Reservoirs and dams can alter the flow regime of downstream rivers^{30,31,133–138}. The effect of reservoirs depends on the proportion of water retained within the upstream river network and operation schemes. Estimates indicate that reservoirs have led to a net reduction in flow volumes and dampening of the amplitude of the seasonal cycle^{30,31}. The magnitude of the effect on stream flow depends on the size and purpose of individual reservoirs and regional water demand³¹.

Past changes in global river flow

Human influence on river flow can vary substantially depending on the type of human intervention and the flow-generating processes that are affected. These overlapping drivers can lead to various temporal and spatial alterations to stream flow¹³⁹. To synthesize knowledge on past changes in river flow and to identify knowledge gaps, a non-exhaustive typology of possible changes is adopted¹³⁹ (Fig. 2).

The first and most studied category of change involves monotonic trends in flow magnitude, including changes in annual mean, low or high flows (Fig. 2a). An example of this is increasing annual discharge, which can be driven by increasing precipitation. The second category of change involves gradual changes in the (seasonal) amplitude of river flow (Fig. 2b), which might occur in the case of regulation that aims to reduce the differences between the high-flow and low-flow seasons. The third category describes gradual shifts in the timing of the seasonal cycle, in which the occurrence of low or high flow seasons is moved throughout the year (Fig. 2c), for example, due to earlier snow melt. Finally, abrupt changes in river flows, exemplified here by a break point in both the mean and variance (Fig. 2d), are often associated with sudden shifts in water management.

Past changes in river flow are assessed using in situ observations from gauging stations. Despite being the most abundant observations of the terrestrial water cycle¹⁴⁰, the available set of stations was not built as a systematic network and, as a consequence, is unevenly distributed around the world, with a disproportional number of stations in large, perennial and more densely populated watersheds¹⁴¹. This placement bias is amplified by both declining monitoring networks¹⁴² and latency in data mobilization, notably in less developed countries or regions (Box 1). To overcome these spatial sampling biases, there might be some benefit to augmenting station-based data with re-analysis-based global reconstructions of river flow. However, trends for several water cycle components based on re-analysis can be unbalanced at the global scale¹⁴³ and non-homogeneous^{144,145}. As a consequence, model-based trend estimates of both local runoff⁷⁸, river flow^{146,21,146} and other terrestrial water variables¹⁴⁷ are uncertain and can even have opposing trend directions in some world regions⁷⁸.

At the scale of individual stream flow gauging stations, observed trends can vary greatly between locations due to natural variability in atmospheric drivers, highly variable terrestrial processes and in response to localized effects of water management^{15,17,148,149}. In addition, statistical trend testing at individual locations lacks the power to identify weak but spatially consistent change patterns¹⁵⁰ such as the emerging effects of human influence on the climate system. However, when aggregating local trend estimates to regional scales, robust patterns of change emerge in the global observational record^{17,18,22}. The

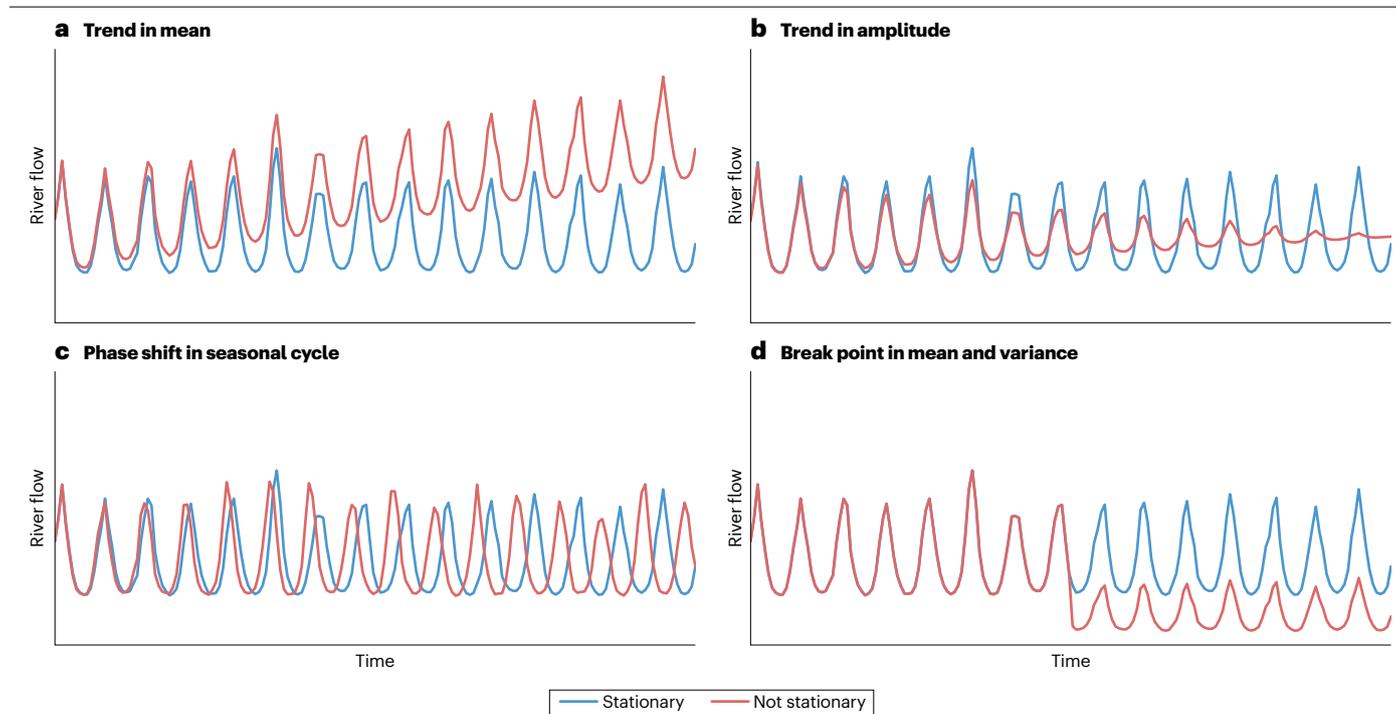


Fig. 2 | A typology of changes in river flow. a–d, Different processes can result in a multitude of changes in river flow dynamics. Illustrated here are a gradual trend in the mean (a), a gradual change in the amplitude of the seasonal cycle

(b), a gradual phase shift in the seasonal cycle (c) and a sudden break point in mean and variance (d). The changes illustrated are indicative of different categories but not exhaustive. Note that the different types of changes can coincide.

following assessment therefore focuses on the dominant direction of changes in reference regions defined for the sixth assessment report for the intergovernmental panel on climate change (IPCC)¹⁵¹ (Fig. 3 and Supplementary Fig. 1).

Owing to the steadily evolving nature of the Earth system, trend estimates in river flow are sensitive to the selected start and end dates of the analysis^{17,115,152}, highlighting the role of natural decadal variability in the Earth system^{14,153–155}. Acknowledging this variability, the following assessment focuses on developing a comprehensive picture of changes in river flow over the past decades. To this end, sources based on observations covering a time frame that ranges at least until the year 2010 are primarily considered. Findings from the literature are supplemented with updated trend analyses of in situ observations from the Global Runoff Data Centre, the African Database of Hydrometric Indices¹⁵⁶, and comprehensive stream flow collections for India (CAMELS-IND)¹⁵⁷, China¹⁵⁸ and Russia¹⁵⁹, using published methods^{17,22} for the time period 1971–2020 (Supplementary Note 1 and Supplementary Fig. 2). However, note that that despite these data-mobilization efforts, the considered stations do not cover large parts of Africa and Asia, preventing an observational assessment in these regions.

Observed trends in annual river flow

Mean annual river flow is a key indicator of water availability. Observed trends in annual river flow between 1971 and 2020 reveal regions with predominantly increasing or decreasing river flow (Fig. 3a,b and Supplementary Table 1). In the northern high latitudes and in parts of central Asia, as well as northern South America, river flow has significantly increased in 1971–2020. Significantly decreasing river flow is found in central Europe

and the Mediterranean, central South America, the Indian subcontinent, East Asia, southern and eastern Australia, and New Zealand.

To balance spatial biases in the observational data, previously documented global^{14–17,19–21,160} and (sub) continental^{158,159,161–169} patterns of changes in river flow are considered (Fig. 3c, Supplementary Tables 2 and 3 and Supplementary Note 2). In several regions, the direction of assessed change in annual river flow differs between the quantitative trend assessment (Fig. 3b) and the meta-analysis (Fig. 3c). The reasons for these inconsistencies include, but are not limited to, differences in the considered time windows, differences in the considered stations, methodological differences across studies and inevitable uncertainties that arise when inferring dominant directions of change visually from maps. Instances in which both the regional trend analysis and the meta-analysis yield robust (respectively statistical significance and high agreement across sources) but opposing change directions include northeastern North America and northern Europe. In these regions, the trend assessment shows significantly increasing river flow, but combined evidence from prior studies indicates no change.

Continental-scale to global-scale patterns of change in past low, mean and high annual river flow are broadly captured by global hydrological models driven with atmospheric forcing data, even if local water use and land use are not accounted for¹⁸ and despite uncertainties in re-analysis-based runoff trends (Box 1). Similarly, changes in flow volumes are correlated with changes in precipitation in more than two-thirds of the world's largest rivers^{160,170}. Overall, the above evidence suggests that changing atmospheric conditions (such as precipitation and factors affecting evapotranspiration) are dominant drivers of past changes in river flow volumes at continental to global scales, which is

consistent with the finding that many managed and natural catchments react similarly to climate change¹⁶⁸.

As global-scale changes in river flow are linked to atmospheric conditions, the question arises whether human influence on the climate system contributes to the observed pattern of change. Climate change detection and attribution techniques that combine observational and model-based evidence to distinguish emerging change patterns from internal climate variability are used for this purpose^{53,171}. Global and regional spatial change patterns in annual low¹⁸, mean^{18,21,34,172} and high¹⁸ flows are consistent with climate model simulations that consider the effect of human emissions – including both greenhouse gases and aerosols – on the climate system, and that observed spatial trend patterns cannot be explained by natural climate variability alone.

Box 1 | Data for quantifying changes in past river flow

In situ observations

River flow is the component of the terrestrial part of the water cycle that is best monitored by in situ observations^{140,252}, with a greater abundance of gauging stations than data from variables such as soil moisture³⁰⁰ or evapotranspiration³⁰¹. In addition, river flow observations cover, in general, longer time periods than these other hydrological variables. The Global Runoff Data Centre holds a large collection of daily river flow time-series data from around the globe. However, although the Global Runoff Data Centre collection has been updated lately in the Americas, Europe, southern Africa and Australasia, there are fewer stations with up-to-date coverage in large parts of Africa and Asia. Despite efforts to combine regional data sources into global collections^{20,203,253–255}, the uneven spatial and temporal coverage of available observations¹⁴¹, together with a decline of monitoring networks in several world regions¹⁴², remains a key limitation when assessing global changes in river flow.

Model-based reconstructions of river flow

Model-based reconstructions or re-analysis of runoff and river flow with global coverage allow for insights into past changes at locations not covered by in situ observations³⁰². These reconstructions rely on physics-based^{220,265,266,303–306} or data-driven models^{14,181,271} that predict runoff and sometimes river flow as a function of gridded precipitation, temperature and other atmospheric drivers with global coverage^{143,307–309}. However, water cycle estimates from atmospheric re-analysis can suffer from apparent inhomogeneities^{144,145}, which may cause spurious trends³¹⁰. Moreover, uncertainty of gridded atmospheric data propagates through runoff and river flow models^{146,261,311}, and runoff is particularly sensitive to uncertain precipitation estimates³¹¹. As a result, river flow trends from re-analysis can exhibit systematic errors that depend on the atmospheric inputs^{16,21,146} and runoff trends from different re-analysis-based products can differ even in the direction of change for some regions⁷⁸. Therefore, river flow trends from model-based reconstructions need to be interpreted with caution and are not considered in this Review. Note, however, that regional trends in some re-analysis products do correspond with observational trends if modelled data are masked to match observational coverage^{18,21}.

However, there are only few detection and attribution studies targeting changes in yearly mean river flow, and those that exist focus either on the net anthropogenic forcing including greenhouse gas and aerosol emissions³⁴ or on total historical radiative forcing, which incorporates natural factors such as the influence of large volcanic eruptions¹⁸. Therefore, the available evidence does not permit a clear-cut distinction between the effects of the respective factors. However, consolidating knowledge of how human influence on the climate system and natural radiative forcing affect both precipitation and evapotranspiration provides additional insight. There is substantial evidence of the influence of greenhouse gas and aerosols forcing on large-scale changes in precipitation^{8,53,57,173} and evapotranspiration^{8,53,64,67}, which are directly linked to runoff and river flow through the land–water balance. Additionally, there is emerging evidence on the influence of global dimming and brightening in response to aerosol emissions on Northern Hemisphere river flow¹⁷⁴ and some evidence of a short-lived, yet globally distinct response of river flow to increased aerosols following large volcanic eruptions¹⁷⁵.

Many of the regions that are assessed to have declining river flow also coincide with regions of global irrigation expansion^{118,123} and there is growing regional evidence that declining river flow might be aggravated by irrigation^{110,176}. Overall, this spatial association highlights that water abstractions can contribute to the declining regional river flow, although the superimposition of climate driven drying and increased irrigation¹²³ hampers an unambiguous separation of both factors from a purely observational perspective. Model simulations indicate that water abstraction from irrigation might indeed lead to declining regional runoff, albeit with uncertainties related to different irrigation parameterizations across models^{12,101,177,178}.

Observed trends in annual low and high flows

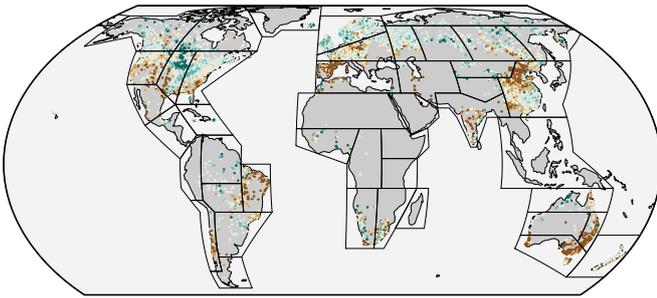
Changes in river flow extremes are often characterized by indicators for the largest and the lowest flows, such as the annual minima or maxima as well as low (5th) and high (95th) percentiles. Annual low, mean and high river flow has changed concurrently in several world regions over the past decades^{17,18,168,179}. This similarity indicates that regional wetting and drying patterns can propagate to the magnitude of hydrological extremes, albeit with some spatial variability at smaller scales. Regionally coherent trend patterns for low, mean and high flows are, for example, found in North America^{17,168}, parts of South America^{17,164}, the Mediterranean^{17,179} and southern Australia^{17,180}. However, in other regions, trends in mean and extreme flows can be disconnected, as illustrated by increasing annual mean flows and decreasing annual maximum flows in parts of Russia¹⁵⁹.

Observed trends in amplitude and phase of the seasonal cycle

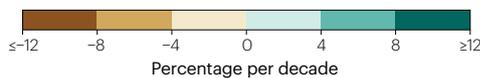
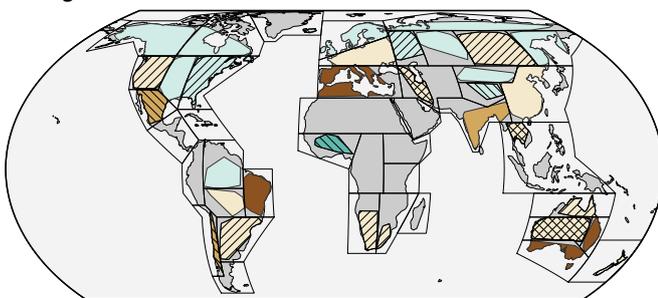
River flow often has a pronounced seasonal cycle that is determined by precipitation, evapotranspiration and storage processes^{22,29,133,181}. In cold regions, low flows are often associated with snow accumulation and high flows with snow melt^{22,181,182}. In other regions, the low-flow season is either associated with low precipitation or high evapotranspiration rates, whereas high flows often coincide with the dominant precipitation season^{22,133,183,184}. At the global scale, an increasing number of locations have changing river flow seasonality²⁹ that is characterized by both changes in amplitude¹³³ and timing²².

Declining seasonal amplitudes, characterized by decreasing differences between wet-season and dry-season river flow, are reported for many stations, although increasing seasonal amplitudes have also been found for some basins¹³³. The tendency for declining seasonal

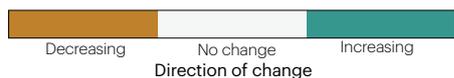
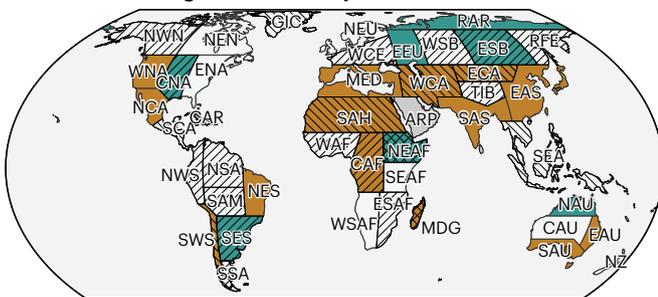
a Observed trend in mean flow



b Regional median trend in mean flow



c Direction of change assessed from prior studies



amplitudes is most pronounced in the Northern Hemisphere and is associated with changes in climate conditions, snow dynamics and water management^{29,30,133,182}, which is corroborated by seasonal trend analyses for several regions including Europe^{179,185}, Siberia¹⁶⁹ and New Zealand¹⁸⁶ that report increasing river flow in the cold season and decreasing river flow in the warm season.

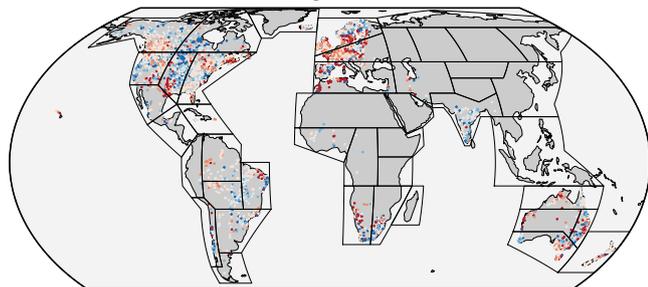
Changes in the phase – or the timing – of the seasonal cycle of river flow are often characterized by trends in the centre timing (also referred to as half-flow date or centre of mass) metric that measures

Fig. 3 | Past changes in river flow volumes over the past decades. **a**, The observed trends in annual mean river flow for the period 1971–2020. Most data stem from the Global Runoff Data Centre. To mitigate spatial biases in station coverage, Global Runoff Data Centre data are supplemented with daily river flow observations contributing to the African Database of Hydrometric Indices¹⁵⁶ as well as a re-computation of previously published trends in annual mean river flow in China¹⁵⁸ and Russia¹⁵⁹ (see also Supplementary Note 1 and Supplementary Fig. 2). **b**, The regional median trends for regions with at least ten gauging stations. The significance of the regional median trends was tested using bootstrapping¹⁷. Hatching indicates a nonsignificant trend (regional mean trend encapsulated in the 10–90% percentile interval of the bootstrap distribution, that is, $P < 0.1$) or regions with few stations. See Supplementary Note 1 for details. **c**, The assessed direction of change in mean river flow based on a synthesis of published large-scale studies that cover the year 2010 and report changes in river flow at continental to global scales (Supplementary Note 2). The set of considered publications are referred to as the number of sources. Note that the considered sources cover different time frames, have different spatial extents and that all sources are weighted equally. The median record length is 40 years and the earliest and latest years considered are 1930 and 2022. The colour coding indicates the assessed direction of past change in river flow volumes. Hatching indicates either that only a few sources are considered or low agreement among sources in the direction of change (less than two-thirds of sources agree on direction of change). ARP, Arabian Peninsula; CAF, Central Africa; CAR, Caribbean; CAU, central Australia; CNA, central North America; EAS, East Asia; EAU, eastern Australia; ECA, eastern central Asia; EEU, eastern Europe; ENA, eastern North America; ESAF, eastern southern Africa; ESB, eastern Siberia; GIC, Greenland/Iceland; MDG, Madagascar; MED, Mediterranean; NAU, northern Australia; NCA, northern Central America; NEAF, northeast Africa; NEN, northeastern North America; NES, northeastern South America; NEU, northern Europe; NSA, northern South America; NWN, northwestern North America; NWS, northwestern South America; NZ, New Zealand; RAR, Russian Arctic; RFE, Russian Far East; SAH, Sahara; SAM, South American monsoon; SAS, South Asia; SAU, southern Australia; SCA, southern Central America; SEA, Southeast Asia; SEAF, southeastern Africa; SES, southeastern South America; SSA, southern South America; SWS, southwestern South America; TIB, Tibetan Plateau; WAF, West Africa; WCA, western and central Asia; WCE, western and central Europe; WNA, western North America; WSAF, western southern Africa; WSB, western Siberia.

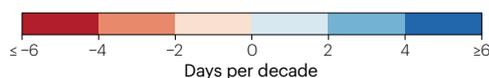
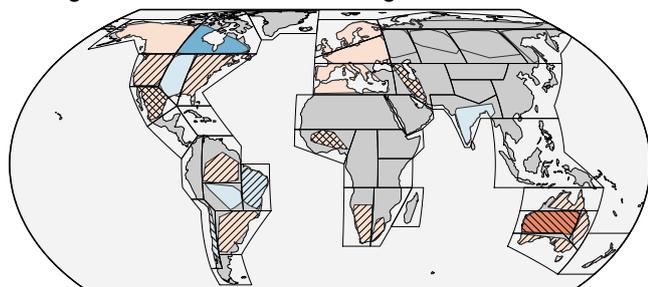
the day of the (hydrological) year at which half of the total annual discharge has occurred^{22,182,187,188}. Reported changes²² are supported by a re-assessment of the 1971–2020 time window (Fig. 4 and Supplementary Note 1). Shifts to earlier river flow timing are observed for several regions in the Northern Hemisphere in which snow melt can have a strong contribution, although a deviation from this pattern occurs in northeastern North America and central North America. The tendency towards earlier timing in snowy regions is consistent across global and hemispheric studies, which conclude that increasing temperatures are associated with smaller snowfall fraction and earlier melting of snow and ice^{22,182,189}, although with some heterogeneity in the response¹⁹⁰. Similar conclusions have been reached in the USA^{188,191–193}, Canada^{194–196}, the Eurasian Arctic¹⁶³ and Europe^{197–199}, although reservoir operation can dominate downstream of large dams¹³⁴. Formal detection and attribution work has demonstrated that changes in stream flow timing and related metrics in snowy climates are only consistent with climate model simulations that account for human influence on the climate system^{29,188,191,195}.

In other regions, changes in the timing of stream flow seasonality follow more complex spatial patterns that are usually linked to an interplay of shifts in precipitation, evapotranspiration and soil moisture^{22,197,200}. Significant trends to later timing are found in parts of

a Observed trend in centre timing



b Regional median trend in centre timing



Less than 50 stations

Regional trend not significant

Fig. 4 | Observed trends in the timing of the seasonal cycle in river flow for the period 1971–2020. **a**, Trends in the timing of the seasonal cycle are based on the centre timing, defined as the day in the hydrological year at which half of the total annual flow has passed the gauge²². Most data stem from the Global Runoff Data Centre. To mitigate spatial biases in station coverage, Global Runoff Data Centre data are supplemented with daily river flow observations contributing to the African Database of Hydrometric Indices¹⁵⁶. Data from China and Russia were only available in yearly or monthly resolution and so could not be reported here (see also Supplementary Note 1 and Supplementary Fig. 2.) Trends in centre timing are estimated using a robust estimator (Sen's slope) and expressed as days per decade, with negative values indicating an earlier timing. **b**, The regional medians for regions with at least ten stations. Significance of the regional median trends is tested using a bootstrapping procedure¹⁷. Hatching indicates a nonsignificant trend (regional mean trend encapsulated in the 10–90% percentile interval of the bootstrap distribution, that is, $P < 0.1$) or regions with few stations.

South America and South Asia, whereas a significant trend to earlier timing is found for the Mediterranean. Most other regions including parts of Africa, Australia and New Zealand have a weak tendency towards earlier timing.

Abrupt changes in past river flow

Time series of in situ observations of river flow can exhibit abrupt changes, or breakpoints. Abrupt changes often occur in response to human interventions such as the construction of dams or the onset of water diversions, but can also occur in response to natural disturbances such as wildfires. Such abrupt changes are often characterized by shifts in either mean flow, the variability of flow or their combination.

Overall, there is scarce systematic evidence of breakpoints in the global observational record²⁰¹. It has been estimated that just below 20% of global river flow time series have strong evidence for a change point²⁰¹, although it is unclear to what extent this measure reflects gradual or sudden changes. Similarly, several assessments of the statistical homogeneity of observational time series report that more than 10% of available monthly stream flow time series might have abrupt changes in European²⁰² and global^{181,203} data collections. Abrupt changes are often assessed in detail in case studies that focus on individual river systems in relation to the construction of dams^{204–208}, but such studies do not allow for a systematic evaluation of the occurrence of frequency breakpoints at the global scale. In addition, studies assessing large samples of river flow time series globally²⁰¹, in the USA^{209,210}, Canada²¹¹, Brazil²¹², Turkey²¹³, Mongolia²⁰⁸ and Russia¹⁵⁹ report change points across stations that are often coherent in space and time. This alignment points towards common atmospheric drivers²⁰¹ and suggests that these might not represent abrupt changes but are rather expressions of decadal climate variability^{14,153–155}, leading to phenomena such as long drought episodes¹⁶⁵. Moreover, it has been noted that many available tools lack the sensitivity to clearly distinguish step changes from trends²¹⁴.

Future changes in global river flow

Future projections of global river flow are based on Earth system models (ESMs) that simulate the response of the Earth's climate to emission scenarios^{215,216}. ESMs compute runoff in their land-surface modules that consider vegetation dynamics, which can be fed into global routing models to derive river discharge^{23,25,27}. A second approach is 'offline' simulations based on atmospheric variables from ESMs to drive dedicated global hydrological models (GHMs) or land surface models that compute both runoff and river flow^{24,217–221}. To ensure consistent assessments, ESM projections are conducted in systematic experiments coordinated through the Coupled Model Intercomparison Project (CMIP)^{222,223}.

Similarly, the Intersectoral Impact Model Intercomparison Project (ISIMIP) coordinates standardized modelling experiments in which bias-adjusted²²⁴ CMIP outputs are fed into GHMs or land surface models^{28,217,219,220}. Any climate projection is prone to uncertainties related to internal climate variability (that is, the irreducible natural variations of the climate system), model uncertainty and emission scenarios^{225,226}. For runoff and related terrestrial water variables, model uncertainty is prevalent in most world regions¹⁰. The following sections focus on results derived from the fifth (CMIP5)²²² and sixth (CMIP6)²²³ phases of CMIP and on the ISIMIP simulations based on them^{28,217,219,220} to ensure a timely assessment. However, note that literature pre-dating these efforts has yielded qualitatively consistent results^{227,228}.

Climate projections are typically communicated with a focus on representing the mean response of an ensemble of model simulations, alongside some measure of model agreement. This approach focuses on the expected climate response. However, it does not provide information on the expected range of possible future outcomes that are linked to internal climate variability and model uncertainties. Consequently, such representations are, for example, not indicative of risks related to physically plausible diverging but equally likely model trajectories²²⁹, a factor that must be kept in mind for the following discussion.

Future changes in annual river flow volume

Total global runoff is projected to increase in response to global warming, but there are also substantial regional and seasonal variations^{7,8,62,230}. Spatially resolved projections of future grid-cell runoff derived from ESMs^{8,61,62,231} and GHMs driven by ESM outputs^{217,218} reveal systematic

changes, albeit with major uncertainties related to the choice of emissions scenarios, internal climate variability, and the structure of the climate and hydrological models^{10,62,217,226}. ESM uncertainty is found to be a dominating factor in CMIP6-based runoff projections, which is particularly pronounced in tropical regions¹⁰. Moreover, differences in the time periods used to quantify projected change hamper a comparison across studies.

Acknowledging these limitations, the focus of this assessment is on whether the considered ensembles suggest an overall increase or decrease in runoff and river flow in specific regions instead of a detailed quantification of the magnitude changes. Climate models project increasing runoff across roughly 70% of the global land area (excluding Antarctica and Greenland)^{10,230}. This increase predominantly occurs in the high northern latitudes, eastern and southern Asia and tropical Africa. Decreasing runoff is found in Central America, tropical South America, the Mediterranean and the southern tip of Africa, corresponding to approximately 30% of global land (excluding Greenland and Antarctica)^{10,62,230}.

Future projections of changes in annual river flow in response to human emissions based on routing runoff rates from ESMs through the global river network^{23,25,27,223,232} (Fig. 5 and Supplementary Note 3), or by driving GHMs with atmospheric data from ESMs^{24,28,218} and from multi-source assessments⁷, reveal regions of increasing and decreasing river flow at the global scale in response to human influence on the climate system. Overall, projected changes in river flow follow local runoff rates, but some features are propagated along the river network. World regions with model agreement for increasing river flow include the northern high latitudes, Asia, a small part of South America and central Africa. Drying regions, in which river flow is projected to decline, include Central America, large parts of South America and the Mediterranean.

Note, however, that marked differences can occur when comparing different model ensembles. For example, ensemble-average changes of routed Global Climate Model (GCM) runoff over tropical Africa and central Australia find increasing annual river flow^{27,233}, whereas changes derived from global hydrology models driven with bias-corrected GCM data suggest drying conditions^{28,233}. Although the reason for such discrepancies remains to be explored in detail, it is interesting to note that projected water cycle changes in the tropics are highly sensitive to the considered GCMs¹⁰ and that 'offline' land–water projections based on processing GCM outputs can exacerbate drying^{234,235}.

Apart from the influence of anthropogenic emissions on the climate system, increasing human water use is also projected to affect terrestrial water systems and with potential implications for river flow volumes in the future¹¹⁷, especially in regions that are projected to see increasingly dry conditions¹² over the next century. In particular, irrigation is expected to increase globally¹¹⁸, which might reduce regional runoff volumes^{12,236,237} and may reinforce hydrological droughts on the Arab Peninsula, parts of central Asia and the Indian subcontinent^{238,239}.

Future changes in annual low and high flows

Low, mean and high flows are projected to change concurrently across many regions around the world^{27,28}. Projections of annual low and high flows, respectively defined as the 5th and 95th percentile of daily river flows^{27,28}, broadly reflect changes in yearly mean flow (Fig. 5), albeit with some regional discrepancies that might also be caused by model uncertainties^{27,28}. However, projected changes in return periods of annual maximum river flow suggest a different pattern: an increase in flood frequency in large parts of tropical Africa and tropical South America, as well as in southern, southeastern and east Asia; and a

decrease in flood frequency in northern and eastern Europe, central Asia and western Siberia^{25,26,240}. Note, however, that decreases are mostly found for moderate floods, whereas there is growing evidence that the most extreme floods will also increase in Europe²⁴¹.

Future changes in seasonal river flow

Climate models project that runoff and thus river flows are not expected to change uniformly across the seasons in response to anthropogenic emissions in all world regions. The contrast is strongest between boreal winter (December, January and February) and summer (June, July and August) in northern high latitudes^{8,10,61,230} (Fig. 6), whereas other regions and seasons largely follow the change pattern of mean annual river flow (Fig. 5). In boreal winter, pronounced runoff increases are projected in the mid-northern latitudes and large parts of Asia, with substantial agreement across the considered model ensemble, which is contrasted by markedly weaker signals and limited model agreement in the boreal summer, which might even see decreasing runoff in the northern high latitudes. This pattern is similar to projected changes in seasonal precipitation across northern mid-latitudes to high latitudes^{8,61}. Moreover, this pattern is probably aggravated by the projected increase in evapotranspiration⁸ and decreasing seasonal snow cover⁸³, which has been associated with robust earlier peak runoff timing in snowy regions across the USA in response to global warming²⁴².

Summary and future perspectives

River flow is an essential component of the Earth system, driven by atmospheric supply and demand of water and modulated by terrestrial processes. Here, we have reviewed the available information on past and future changes in global river flow, with a focus on gradual changes in annual mean flow volumes and changes in seasonality. In addition, emerging evidence on the prevalence of sudden changes in past flow dynamics was considered. Floods and hydrological droughts are covered extensively elsewhere^{42,43,240,243}. Note that low, mean and high flows have been observed to increase or decrease concurrently in many world regions^{17,18,164,168,179,180,234} and are projected to continue doing so in the future^{27,28}.

Anthropogenic climate change, the effect of elevated CO₂ concentration on the biosphere, human interventions in the terrestrial environment and water management can affect river flow at the global scale. Emerging planetary-scale patterns of change in mean river flow and shifts in river flow seasonality in cold regions are linked to changes in atmospheric drivers and can probably be attributed to anthropogenic climate change. Although increasing CO₂ levels are affecting global vegetation and thus evapotranspiration rates, the net effects on global river flow remain subject to ongoing research. Model estimates indicate that large-scale water abstractions (primarily for irrigation) reduce discharge to the oceans by 2–3%^{32,101,125,126} and the global pattern of irrigated areas is correlated with past declines in river flow in several regions. Finally, reservoirs and dams can be associated with shifts in flow regimes, although reductions of flow volumes have also been reported^{30,31,133–138}. However, the strength of these effects is often largest in the vicinity of reservoirs and depends on the ratio of water being impounded relative to river flow.

Climate change versus other human influences on river flow

Advancing understanding of the processes and drivers of river flow is essential for putting observed trends into context and for anticipating future changes. Although this Review highlights the extent of the accumulated evidence on past and future changes in global river flow,

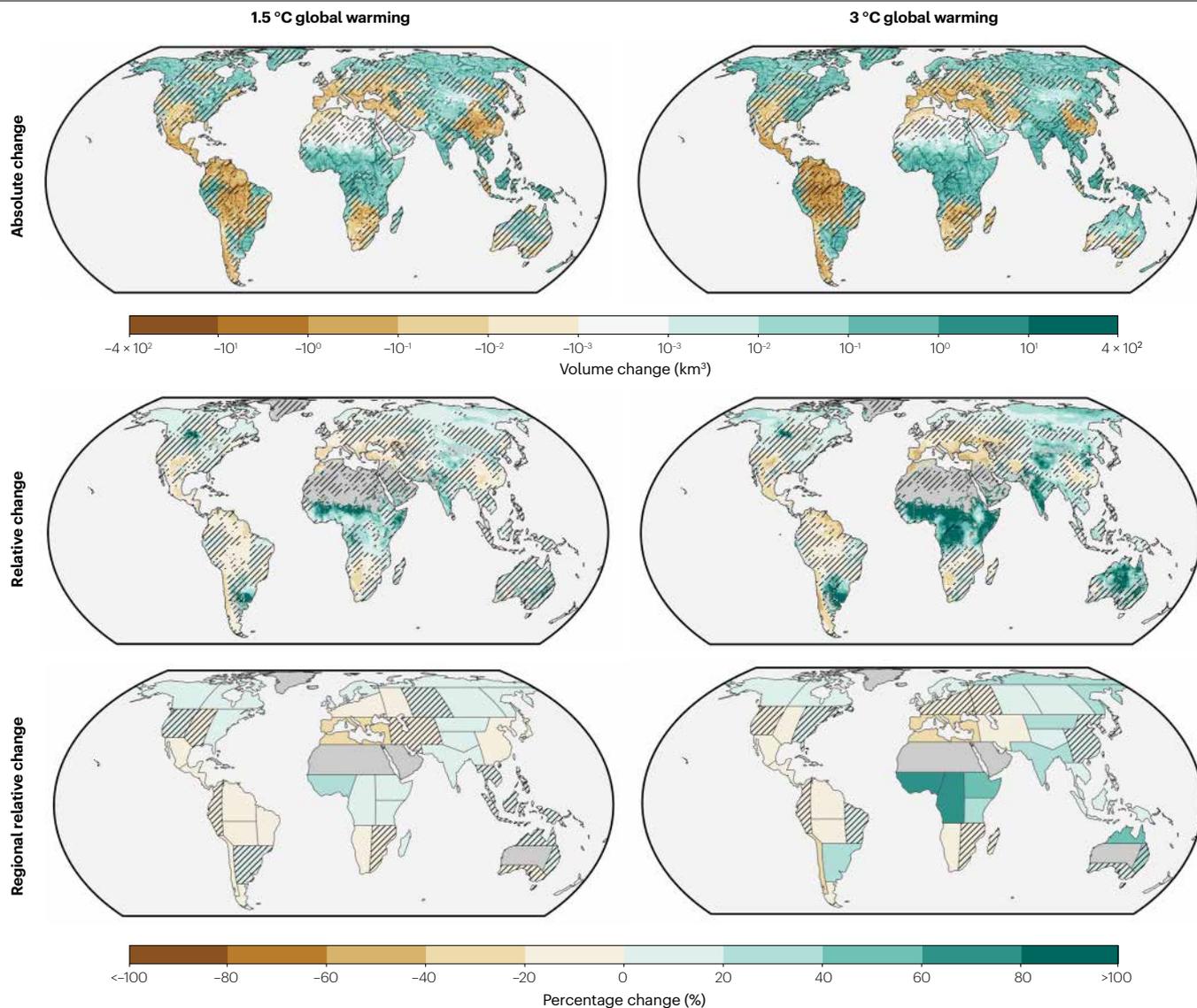


Fig. 5 | Future change in annual mean global river flow for 1.5°C and 3°C global warming. The simulations follow a previous assessment²⁵ that routes runoff from historical and future simulations from eight Earth system models (ESMs) through the CaMa-Flood model²³² (Supplementary Note 3). ESM simulations originate from the sixth Coupled Model Intercomparison Project archive²²³ and assume historical radiative forcing until 2014 and radiative forcing following Shared Socioeconomic Pathway 585 thereafter. Ensemble mean changes are shown for degrees of global warming with respect to the pre-industrial mean (1850–1900)^{62,299}. Relative changes are computed by dividing

the absolute changes through the model-specific grid-cell mean from the base period. In this case, grid cells with close to zero runoff in the base period are masked out before computing the relative change to avoid unstable values related to zero division. Regions dominated by ice caps or extremely arid regions are left blank. Hatching indicates grid cells and regions where fewer than six out of eight ensemble members agree on the direction of change. The analysis highlights that anthropogenic global warming is projected to alter river flow around the world, where some regions are expected to see increasing and others decreasing flow volumes.

there remain pronounced knowledge gaps that need to be addressed, considering an ever-increasing human imprint on the Earth system.

So far, few efforts have examined the combined effect of climate change, human land use and water management on river flow at large scales^{11,12,18,30,110,134,244–246}. Moreover, findings have been inconsistent, hinting at an unconsolidated understanding of how these factors interact. For example, warmer temperatures are changing snow dynamics and can thus alter the seasonal cycle of river flow at the continental

scale²⁹. On the other hand, in the vicinity of reservoirs, flow regulation can have a larger influence on river flow regimes than climate change in snow-fed rivers¹³⁴. Moreover, in regions with decreasing precipitation or increasing atmospheric evaporative demand, reduced water availability might be compensated by increased irrigation, potentially further accelerating drying^{110,176}. These and similar examples highlight that knowledge on the respective roles of anthropogenic climate change and direct human intervention in past and future changes in global river

flow is not fully developed. This apparent gap poses a major limitation for anticipating and adapting to changes in river flow and emphasizes the need to further advance understanding of changes in river flow and its drivers at regional to global scales.

Attributing observed changes in global river flow

Despite increasing knowledge of observed changes in river flow, systematic assessments of the key drivers remain scarce at the global scale, and often focus on the treatment of isolated factors such as the influence of reservoirs^{30,31} or the overarching effects of anthropogenic climate change^{18,29}. To further advance understanding of the most essential drivers of large-scale changes in hydrological systems, a consolidated theory for attributing observed changes is needed – one that is rooted in physical understanding and accounts for both the large degree of natural climate and environmental variability as well as observational and model-structural uncertainty. Such a theory should be built on consolidating concepts of climate and climate-impact attribution^{53,247} that are centred around explicitly formulated working hypotheses and a systematic integration of both observational and simulated evidence.

Attribution methods are centred around factorial simulation experiments that include and exclude the hypothesized driver of change and distinct assumptions of background variability. Attribution to anthropogenic climate change is based on ESM simulations with and without anthropogenic forcing, and attribution is claimed if the expected pattern of change derived from the model experiments is found in the observations given estimates of natural climate

variability^{53,171,247}. This can extend to systematically confronting ESM simulations with observed trends^{248,249}, with specific attention given to regional inconsistencies between observations and simulations²⁵⁰. As internal climate variability can mask emerging climate change signals at the station scale^{35–37}, targeting the emergence of regional to global scale change patterns can enhance signal-to-noise ratios^{18,34}. Focusing on terrestrial processes, impact attribution protocols, for example, provide global hydrology models with raw and detrended atmospheric variables to assess whether an observed change can be linked to trends in the respective atmospheric drivers²¹⁹. Such set ups could be extended to systematically test for the influence of land-cover change and water management, such as by building on advances of modelling the effects of global irrigation expansions in ESM simulations^{178,251}.

Enhancing observational basis

One of the major obstacles for detecting and understanding past changes in global river flow remains the limited accessibility of relevant observations for many regions¹⁴¹. Therefore, strengthening the observational basis is critical. Given that river flow remains the most widely monitored variable of terrestrial hydrosystems^{140,252}, the continued maintenance of observation networks¹⁴², as well as the mobilization and curation of available observations in international collections, is essential. Apart from regularly emerging ad hoc collections^{20,203,253–255}, continued support for the efforts of the Global Runoff Data Centre that is mandated to collect and disseminate hydrological data under the auspices of the World Meteorological Organization remains crucial. This effort should be augmented by data rescue initiatives for hydrological

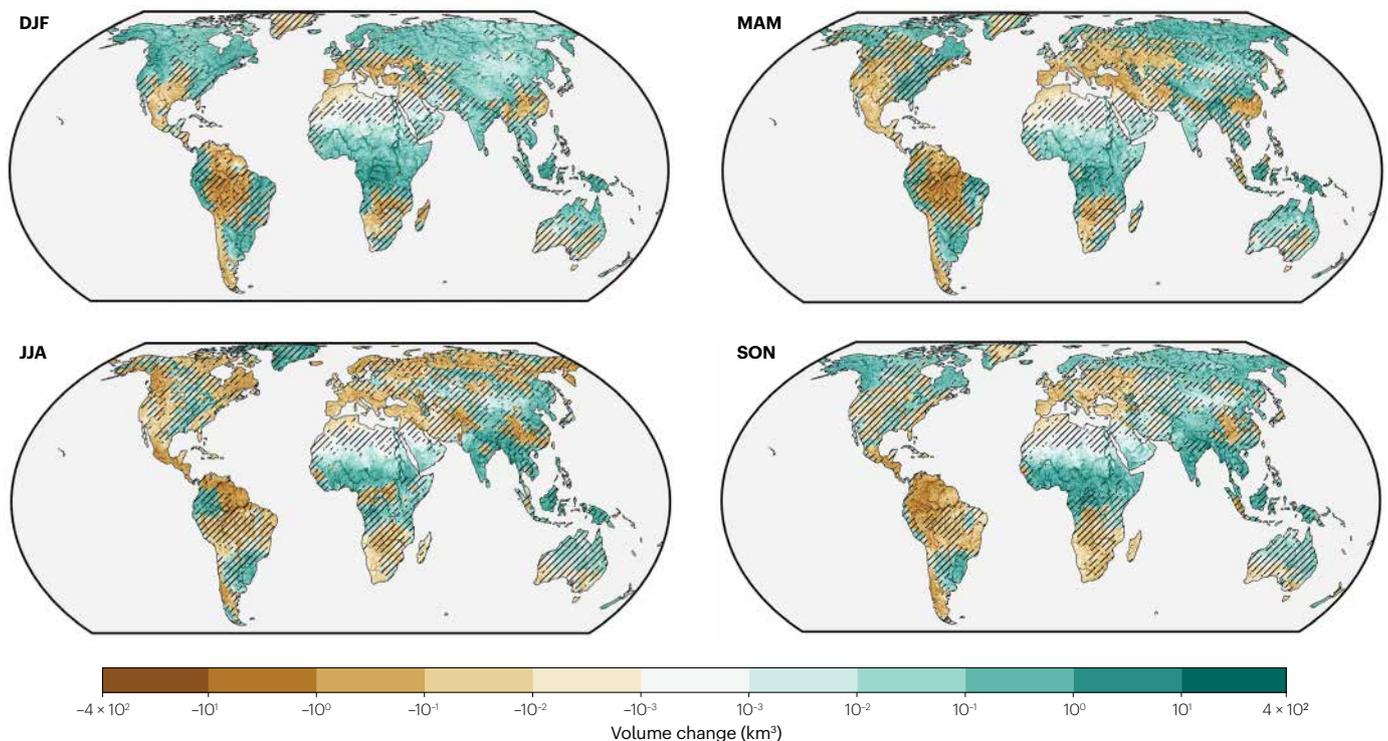


Fig. 6 | Future change in seasonal mean river flow for 3°C global warming. The underlying data and setup are identical to Fig. 5, but evaluated for the mean over December, January and February (DJF); March, April and May (MAM); June, July and August (JJA); and September, October and November (SON). Hatching

indicates grid cells and regions where fewer than six out of eight ensemble members agree on the direction of change. Note the seasonal contrast between boreal winter (DJF) and summer (JJA).

records, building on longstanding efforts in climate science to identify and digitize observational records^{256,257}.

Given that changes in river flow can be the result of both trends in atmospheric variables as well as from water and land management, augmenting the available observations with relevant meta-information is essential. Examples include reference hydrometric networks^{255,258} that focus on compiling long, high-quality records from catchments with little human influence, as well as calls for systematically collecting information on the degree of water management¹³⁷. Moreover, so-called naturalization methods aim to remove the influence of water management from observational time series, although the results can be uncertain and depend on the underlying assumptions²⁵⁹.

Despite best efforts in data mobilization, in situ observations are spatially biased, with incomplete temporal coverage and an under-representation of non-perennial rivers^{20,141,203}. This incomplete spatiotemporal coverage highlights the need to maintain existing observatories and to expand the station network with a focus on locations that optimize information gain^{141,260}. Records can furthermore be supplemented through estimates of past river flow at ungauged locations²⁶¹, for example, by leveraging satellite monitoring of river discharge^{262–264} or through coordinated ensemble modelling efforts^{219,220,265}, supplemented with operational reanalysis^{266,267}. In addition, machine learning has shown promise in estimating runoff and river flow at regional to global scales^{268–272} but challenges remain, including but not limited to extrapolating empirical models to conditions not seen in calibration, developing compatible routing schemes and accounting for water management^{273,274}.

Consolidating model simulations

Current literature on future changes on global runoff and river flow is spread over several communities that operate from different points of departure. On the one hand, future projections of river flow can be based on CMIP-style simulations²²³ and rely on the increasingly refined land-surface components of ESMs that resolve the coupled terrestrial water and energy balance, with increasing capabilities to account for the carbon cycle, land-cover change and vegetation dynamics²⁷⁵. However, ESMs contributing to the CMIP efforts are mostly run at low spatial resolution and do not account for human water management. Moreover, ESMs are often biased and typically do not compute discharge along the global river network, which needs to be computed using distinct routing models^{23,25,26}.

Simultaneously, efforts such as ISIMIP^{219,220} use spatially down-scaled bias-adjusted CMIP simulations to drive GHMs that aim for detailed modelling of terrestrial hydrology, and consider routing and direct human interventions such as water withdrawals or dam operation^{276–278}. However, ISIMIP has so far only considered a reduced set of ESMs as inputs, which might not be sufficient to cleanly isolate an emerging signal from climate model uncertainty and internal variability. Moreover, bias adjustment can tamper with the climate change signal, as well as the physical consistency across variables^{279,280}. In addition, many GHMs rely on ad hoc estimates of evapotranspiration that consider neither the surface energy balance nor plant physiology and might respond too strongly to warming^{235,281}. Finally, a lack of standardization for drainage direction maps renders multimodel comparisons challenging²⁸².

So far, projections of future river flow based either on routing ESM runoff^{23,25,27} or GHM simulations^{24,28,218} have often remained in their disciplinary silos and simulation experiments might not be directly comparable to each other. Therefore, a closer exchange across modelling

communities is essential to tackle the open question of whether differences in projections of future stream flow are due to model uncertainty, inclusion of different processes, artefacts of bias correction or simply related to small ensemble sizes that do not saturate the distribution of internal climate variability.

Ecological and societal effects of changes in river flow

Changes in river flow affect the water level and extent of connected wetlands and lakes²⁸³. Reductions in flow also affect water quality by increasing pollutant concentrations through reduced dilution volume²⁸⁴ that, compounded by increasing water temperatures²⁸⁵, affects both water supply and river biota. A change in the river flow regime²⁸⁶ translates into altered habitat availability and quality, influencing ecological communities and their species composition. Aquatic ecosystems are sensitive to various components of the flow regime and their variability. For example, peak flows can lead to lateral floodplain connectivity, dispersal and habitat complexity, whereas low flows can be particularly important for spawning and recruitment of species²⁸⁷.

Alterations in river flow causing dry periods are particularly disruptive for the river biota²⁸⁸, and both observational trends and future projections point towards drying in many world regions. Understanding the effect of changes in river flow on river biota is complex and often limited to observations²⁸⁹ or to confounding factors in empirical analyses^{289,290}. Yet global scale studies predict that climate change will have a negative effect on most species, with estimates suggesting that ~36% of freshwater fish species will see their range halved under the future climate²⁹¹.

Societies depending on ecosystem services from rivers are most vulnerable to altered river flow and regimes²⁹². Although the effects from changes in the water supply used for agriculture, industry, mining, domestic water use, thermal and hydroelectric power generation²⁹³, and shipping are most direct, effects from changes in water quality and temperature can also be important. Shifts in peak river flow timing and increases in winter stream flow present opportunities for increased power generation, but conversely increased dry days in the summer present power supply risks^{293,294}. The boon of increased river flow, particularly in tropical areas, might improve agricultural production²⁹⁵ but increased drought threatens yields^{296,297} and can create societal conflict due to migration to more arable areas²⁹⁸.

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Author contributions

L.G. set the scope and drafted the article with input from all co-authors. L.G. analysed the data. E.F.-C. and C.W. contributed code for data analysis and visualization. Y.H., D.Y. and X.Z. provided global river flow projections using the CaMa-Flood model. E.F.-C. post-processed global river flow projections. M.B.K. ran scripts to compute trends for Russian data. N.F. and D.M. provided updates and data analyses for Russia. Y.T. provided updated data for Africa. X.L. and K.W. provided data analysis for China. All co-authors contributed with references and edits to the text.

Competing interests

The authors declare no competing interests.

Additional information

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¹Institute for Atmospheric and Climate Sciences, ETH Zürich, Zurich, Switzerland. ²WSL Institute for Snow and Avalanche Research SLF, Davos Dorf, Switzerland. ³Climate Change, Extremes and Natural Hazards in Alpine Regions Research Center CERC, Davos Dorf, Switzerland. ⁴Institute of Physical Geography, Goethe University Frankfurt, Frankfurt am Main, Germany. ⁵Senckenberg Leibniz Biodiversity and Climate Research Centre (SBiK-F), Frankfurt am Main, Germany. ⁶Earth System Science Division, Pacific Northwest National Laboratory, Richland, WA, USA. ⁷Hydrology Department, Faculty of Geography, Lomonosov Moscow State University, Moscow, Russia. ⁸School of Geography, University of Nottingham, Nottingham, UK. ⁹Department of Civil Engineering, Shibaura Institute of Technology, Tokyo, Japan. ¹⁰Center for Information Technologies, BioSense Institute, Novi Sad, Serbia. ¹¹Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, China. ¹²School of Geography and the Environment, University of Oxford, Oxford, UK. ¹³Institute of Environmental Science and Geography, University of Potsdam, Potsdam, Germany. ¹⁴Institute for Environmental Science, RPTU University Kaiserslautern-Landau, Landau, Germany. ¹⁵Espace Dev, Univ. Montpellier, IRD, Montpellier, France. ¹⁶School of Civil Engineering, The University of Sydney, Sydney, New South Wales, Australia. ¹⁷Institute of Industrial Science, The University of Tokyo, Tokyo, Japan. ¹⁸Institute of Hydraulics and Ocean Engineering, Ningbo University, Ningbo, China.